

# Is there spectral variation in the polarized reflectance of leaves?

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## ABSTRACT

The light scattered by plant canopies depends in part on the light scattering/absorbing properties of the leaves and is key to understanding the remote sensing process in the optical domain. Here we specifically looked for evidence of fine spectral detail in the polarized portion of the light reflected from the individual leaves of five species of plants measured at Brewsters angle over the wavelength range 450 to 2300nm. Our results show no strong, unambiguous evidence of narrow band spectral variation of the polarized portion of the reflectance factor.

Key words: Leaf reflectance, polarization, hyperspectral polarization, quasi specular reflection, leaf cuticle, bidirectional reflectance factor BRF

## 1. INTRODUCTION

The light scattered by plant canopies depends in part on the light scattering/absorbing properties of the leaves and is key to understanding the remote sensing process in the optical domain.

While this scattered light may be described by the four components of the Stokes vector<sup>1</sup>, significant progress has been achieved toward understanding only the first component, the intensity of the scattered light. Research shows that the magnitude of the linearly polarized light may be a significant part of the light scattered by some canopies<sup>2</sup>.

In this research we measured the intensity and the linear polarization of the light scattered by single leaves, testing the hypothesis that the polarized light scattered by a leaf is attributable to properties of the surfaces of the leaf and does not depend upon the characteristics of the interior of the leaf, such as its resident chlorophyll<sup>2</sup>. We concentrated analysis efforts on the polarized portion of the reflected light, looking specifically for evidence of fine spectral detail, which, if found, would presumably be linked to the absorbing characteristics of the leaf cuticle. This research extends previous investigations limited to measurements in the 450 to 800 nm wavelength range of the leaves of approximately 20 species typically found in the vicinity of Lafayette, Indiana<sup>3-6</sup>.

## 2. METHODS

We measured, Fig. 1, the detached leaves of five plant species — cannabis plants grown in a greenhouse at the USDA (United States Department of Agriculture), as well as coffee, ficus, philodendron and spathiphyllum plants that were purchased at a local garden store. Following harvest, each leaf petiole remained in a water filled vial to minimize leaf water loss and consequent spectral reflectance changes. In the experimental protocol, three leaves were observed sequentially, Fig. 1, and the resulting spectra averaged.

During data collection, polarized spectral BRF (bidirectional reflectance factor) data were collected, Fig. 1, at equal illumination and observation directions, 55° from leaf normal, approximately Brewsters angle, using an ASD FieldSpec Pro spectroradiometer (Analytical Spectral Devices, Boulder, Colorado, USA) equipped with a 1° FOV fore optic that observed the leaf through a wire grid polarizer (Meadowlark Optics, Frederick, CO, USA) with a wavelength range from 400 nm to 2500 nm. An aperture immediately in front of the ASD fore optic lens limited the observing beam diameter to 1.5cm. The leaf area measured was calculated as the projection of the 1.5cm diameter beam onto the leaf at 55°. A larger area of the leaf was illuminated using a 300 watt radiometric power supply and

lamp (Oriel Instruments, Stratford, CT, USA) operating at 50watts. At one point the fiber optic was removed and the field of view of the fore optics of the ASD spectroradiometer was verified.

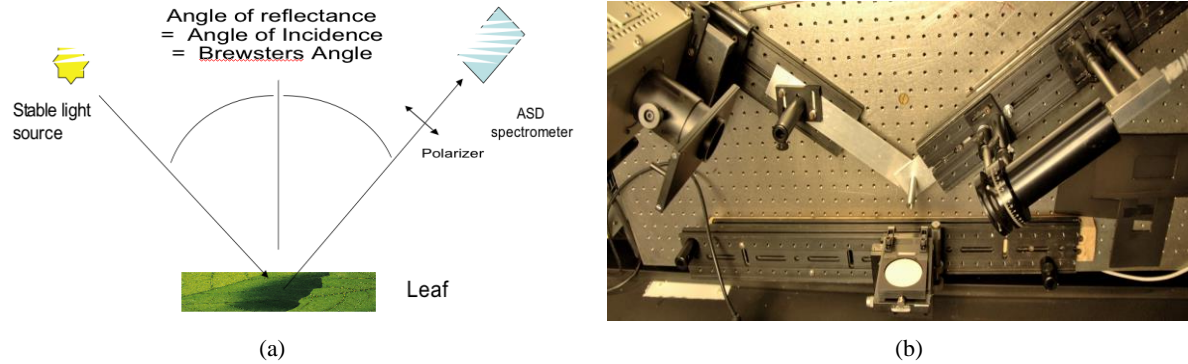


Figure 1. Unpolarized light incident on the leaf was polarized during reflection by the leaf, transmitted by a wire grid polarizer and measured by the spectrometer. For calibration purposes, Fig. 1b, a Spectralon™ calibration surface (Labsphere, North Sutton, NH, USA)(the white oval at lower photo center) was measured in place of the leaf.

The bidirectional reflectance factor (BRF) and the linearly polarized part of the BRF –  $BRF_{QU}$  - of each target  $i$  (either one of five leaf species or a Spectralon™ calibration surface) were calculated from measurements at 11 polarizer angles ( $\theta = -90, -70, -50, -30, -10, 0, 10, 30, 50, 70, 90$  degrees), first regressing (statistical analysis software, SAS 9.4, SAS Institute Inc., Cary, NC, USA) the data,  $X(\lambda, i, \theta)$ , recorded at each wavelength,  $\lambda$ , leaf or Spectralon calibration surface,  $i$ , and polarizer angle,  $\theta$ , using eq. 1 with intercept  $C$

$$X(\lambda, i, \theta) = C(\lambda, i) + A(\lambda, i)\sin(\theta) + B(\lambda, i)\cos(\theta) \quad (1)$$

Rearranging provides

$$X(\lambda, i, \theta) = C(\lambda, i) + \{[A(\lambda, i)^2 + B(\lambda, i)^2]^{0.5}\} \sin(\theta + \theta_0) \quad (2)$$

where  $\theta_0 = \arctan[A(\lambda, i) / B(\lambda, i)]$ . Finally the  $BRF(\lambda, i)$  and  $BRF_{QU}(\lambda, i)$  for target  $i$  were calculated

$$BRF(\lambda, \text{leaf } i) = \frac{BRF(\lambda, \text{Spectralon}) C(\lambda, \text{leaf } i)}{C(\lambda, \text{Spectralon})} \quad (3)$$

$$BRF_{QU}(\lambda, \text{leaf } i) = \frac{BRF(\lambda, \text{Spectralon}) [A(\lambda, \text{leaf } i)^2 + B(\lambda, \text{leaf } i)^2]^{0.5}}{C(\lambda, \text{Spectralon})} \quad (4)$$

We assumed the  $BRF(\lambda, \text{Spectralon}) = 1.0$  for illumination and observation at Brewsters angle.

To search for fine spectral variation in the polarized BRF, we calculated the correlation coefficient of the  $BRF_{QU}$  at three lags. That is, at each wavelength,  $\lambda$ , we correlated the five numbers  $BRF_{QU}(\lambda + y, \text{leaf } 1)$ ,  $BRF_{QU}(\lambda + y, \text{leaf } 2)$ , ...,  $BRF_{QU}(\lambda + y, \text{leaf } 5)$  with the five numbers  $BRF_{QU}(\lambda - y, \text{leaf } 1)$ ,  $BRF_{QU}(\lambda - y, \text{leaf } 2)$ , ...,  $BRF_{QU}(\lambda - y, \text{leaf } 5)$  with  $y = 1, 3$  and  $7\text{nm}$ . The three lags are found:  $2y = 2, 6$  and  $14\text{nm}$ .

### 3. RESULTS

The BRFs of individual leaves, Fig. 2, display variation with wavelength typical of green leaves, revealing a green peak at 555nm and the effects of chlorophyll absorption in the visible wavelength region, 500-700nm, and, in the

reflective infrared spectral region between 700 and 2500 nm, an infrared plateau and the effects of water absorption around 1,400 and 1,900nm.

The  $BRF_{QU}$  of individual leaves, Fig. 3, display no evidence of pigment absorption in the visible region nor water absorption in the reflective infrared region. At wavelengths of 1000 and 1775nm the abrupt changes in the  $BRF_{QU}$  amplitude of the Ficus and to a lessor extent the coffee and the spathiphyllum are calibration artifacts associated with detector changes in the ASD. The amplitude of most spectra generally increases with wavelength. The spathiphyllum and philodendron spectra increase the most - 1.5-2x between 500 and 2500nm - while the cannabis spectra display little if any change with wavelength. At wavelengths near 1350 nm the  $BRF_{QU}$  of most leaves displays a miniature trigonometric sine wave atop an otherwise slowly changing response with wavelength.

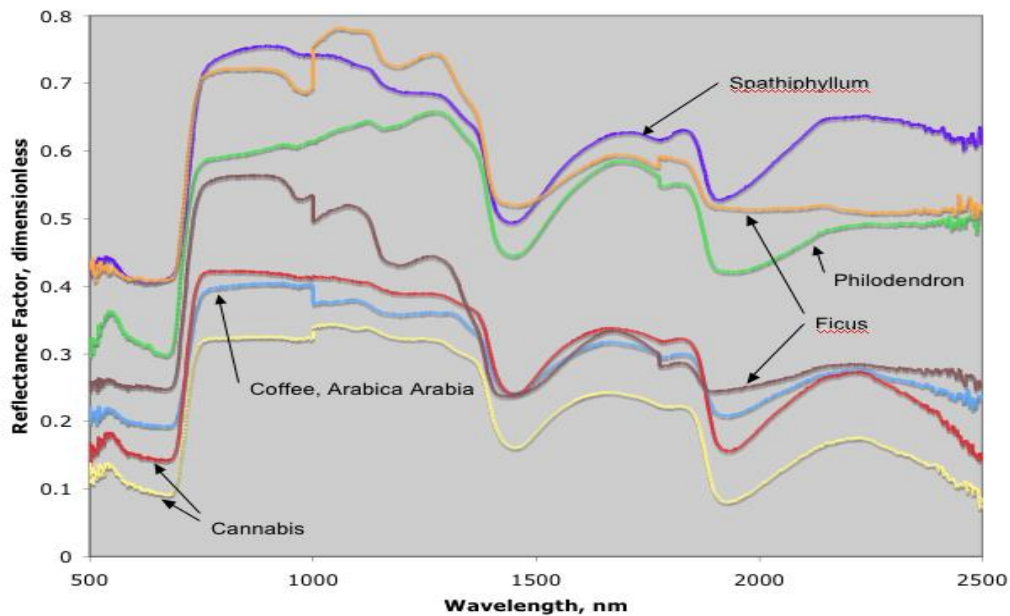


Figure 2. The BRF (bidirectional reflectance factor) was estimated from measurements at Brewsters angle of the leaves of the five plant species

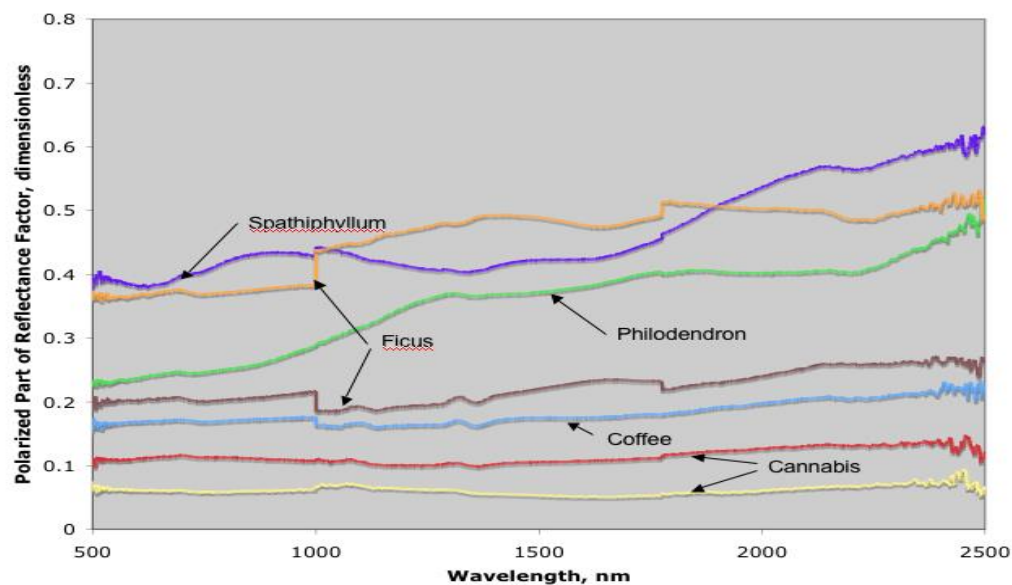


Figure 3. The polarized part of the relative bidirectional reflectance factor ( $BRF_{QU}$ ) was estimated at Brewsters angle for the leaves of the five plant species.

The correlation coefficient provides an extremely sensitive tool in the search for narrow band spectral information. In theory if there is species specific variation within a narrow spectral band, then the correlation coefficient will display a decrease within that narrow band. However, the dramatic variation of the correlation coefficient of the  $BRF_{QU}$ , Fig. 4, requires careful interpretation.

The correlation coefficient depends not only upon variation of the signal – which in this case is species specific spectral variation in the  $BRF_{QU}$ , Fig.3 – but inversely upon the amount of noise in the spectra. Thus, the magnitude of the correlation coefficient is reduced in the 500-600nm and 2300-2500nm wavelength regions where the spectra, Fig. 2, appear noisy. Additionally, the magnitude of the correlation coefficient, Fig. 4, is reduced when the leaf radiance decreases – the values measured before calibration and conversion to BRF and then  $BRF_{QU}$ . This is because when the leaf radiance decreases, the background electrical noise becomes proportionately larger; thus, the minor water absorption bands at 970 and 1200nm and the large water absorption bands at 1450 and 1940nm appear in the correlation coefficient spectrum, Fig. 4, even though these absorption bands do not appear in the  $BRF_{QU}$  spectra, Fig. 3. For similar reasons the correlation coefficient, Fig. 4, decreases at the edge of the chlorophyll absorption band at 700nm, the ‘red edge’ in remote sensing terminology. The decreased values of the correlation coefficient near 1350nm, Fig. 4, probably depend in part on the miniature sinusoids, Fig. 3. Values of the correlation coefficient, Fig. 4, decrease in the vicinity of 1500-1600nm and 2000-2100nm likely due to the smaller leaf radiance values associated with the nearby water absorption bands at 1450 and 1940nm. The two vertical lines (at 1000nm and 1775nm) are analysis artifacts related to detector changes in the spectrometer.

Finally, the reductions of the correlation coefficient within the relatively broad spectral regions 1000-1150nm and 1775-1850nm appear associated with broad band differences in the  $BRF_{QU}$  slopes, which vary from negative to near zero to positive.

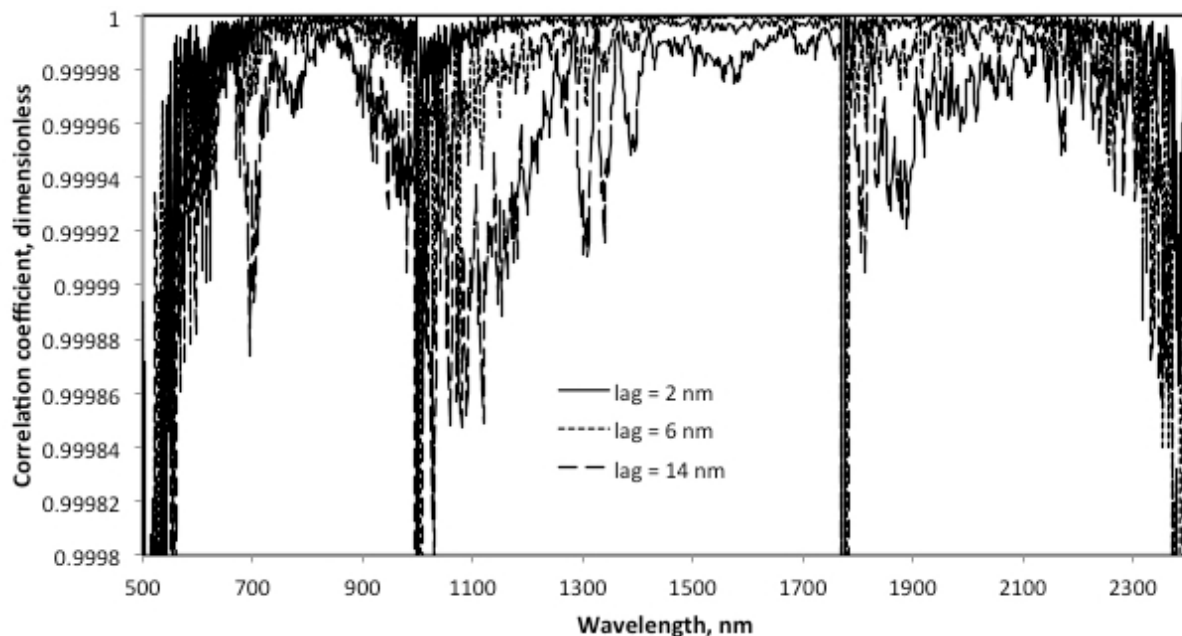


Figure. 4. Correlation coefficient of the  $BRF_{QU}$ , Fig.3, at two wavelengths separated by 2, 6 and 14nm.

#### 4. DISCUSSION

Our results, Figs. 3 and 4, provide no evidence there is hyperspectral variation in the polarized portion of the reflectances,  $BRF_{QU}$  of the leaves of the five species measured, provided we ignore for the moment the miniature sine waves in the spectra, Fig. 3 - more on that below. With that proviso, examination of the  $BRF_{QU}$ , Fig. 3, reveals no species dependent variation within narrow spectral bands. The variation in the correlation coefficient, Fig. 4, while

dramatic, results primarily from the impact of noise in the measurement system, not from hyperspectral variation in the  $BRF_{QU}$ . The broadband slope differences in the  $BRF_{QU}$  between 1000 and 1200nm and between 1775 and 2100, Fig. 3, while not narrow band spectral information, deserve scrutiny in follow-on research involving additional plant species.

While we have identified no hyperspectral information in the  $BRF_{QU}$ , we believe the results, Fig 3, support the view<sup>2</sup> that the polarization of the light incident on the leaf is modified during a quasi specular reflection at the leaf surface, the first surface it encounters. The polarized portion of the reflected light, Fig. 3, never enters the leaf to interact with the pigments and water inside the leaf; thus, the  $BRF_{QU}$  of the leaves, Fig.3, display no evidence of chlorophyll or water absorption, for example. We use the term “quasi specular,” because the leaf surface is not optically smooth. Rather it consists of an amorphous wax substrate partially covered by particles and structures of amorphous and crystalline wax. The particles and structures on the leaf surface vary in size and surface density.

We propose the general increase in the polarization of the  $BRF_{QU}$  with wavelength, Fig. 3, is due to interaction between the wavelength of the incident light and the size and density of the surface particles and structures. Provided the density of the particles and structures on the leaf surface is comparatively low, the leaf surface will more closely approximate an optically smooth surface at long wavelengths, e.g. 2500nm, rather than shorter wavelengths, e.g. 500nm. As the approximation improves, the amount of light specularly reflected should appropriately increase and hence the increase in the  $BRF_{QU}$  toward longer wavelengths. All of this suggests that surface density of particles and structures should be greatest on the cannabis and coffee leaves and much lower on the philodendron and spathiphyllum leaves.

The miniature sine wave at 1350 nm, Fig. 3, is characteristic of the effects of anomalous dispersion, an optical phenomenon that occurs when a light beam is specularly reflected at the surface of an absorbing material<sup>7</sup>. Typically, the magnitude of anomalous dispersion effects after just one specular reflection is small – probably too small to be consequential for remote sensing purposes. Thus, in general we do not expect the light singly specularly reflected by leaves to include the effects of anomalous dispersion, suggesting that the evidence for it displayed in Fig. 3 is due to a source other than the leaf surface.

Measurements of the five leaves using a second spectrometer, a GER 3700 (Spectra Vista Corp., Poughkeepsie, New York, USA) revealed no evidence of the miniature sine wave at 1350nm. The key difference between the two instruments is that the ASD uses a two meter fiber optic to connect fore optics and instrument body while the GER directly connects fore optics and instrument body. The attenuation spectrum, Fig. 5, for the optical glass used in the ASD fiber optic includes a slight absorption at approximately 1350 nm, suggesting the apparent anomalous dispersion effects evident in the  $BRF_{QU}$  are linked to the ASD fiber optic rather than specular reflection at the leaf surface.

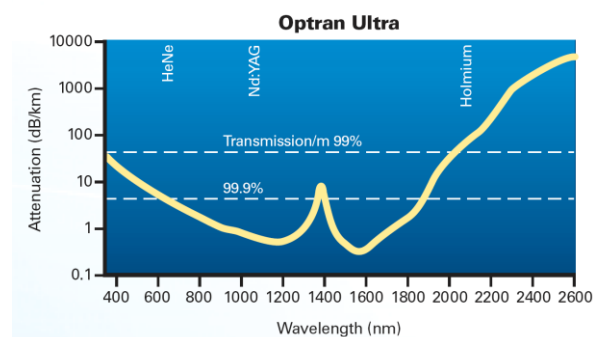


Figure 5. The attenuation of the optical fiber in the ASD instruments shows a minor absorption band at approximately 1350 nm.

It is also important to note that both the detector offsets at 1000nm and 1775nm, Fig. 3, and the presence of the miniature sine waves at 1350nm suggest we should have paid closer attention to our calibration procedures during data collection. The miniature sine wave, if due to anomalous dispersion in the ASD fiber optic, should not appear in  $BRF_{QU}$ , if properly calibrated.

## 5. CONCLUSIONS

We found no evidence of hyperspectral variation in the polarized portion of the reflectance,  $BRF_{QU}$  of the leaves of the five species measured. Our results support the view that leaves polarize incident light during a quasi specular reflection at the leaf surface, the first surface the incident light encounters. Our results show that the polarized portion of the reflected light is reasonably spectrally flat and displays no evidence of interaction with leaf water and pigments such as chlorophyll. This means that polarization measurements may be used to divide the light reflected by a quasi specularly reflecting leaf into two parts – one reflected by the leaf surface and the other reflected by the leaf interior. The polarized portion of the reflectance of several leaf species that we measured increased with wavelength. We propose these leaf surfaces – with their particular particle size distributions and surface densities - more closely approximate an optically smooth surface at longer compared to shorter wavelengths. We do not expect the effects of anomalous dispersion to be evident in the polarized remotely sensed reflectance spectra of leaves.

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